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"Self-sensing TDR with micro-strip line"

Date

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Abstract: Carbon Fiber Reinforced Polymer composites (CFRP composites) have widely used to aerospace components. It is quite difficult to detect delamination cracks visually for the CFRP composites, and the delamination causes degradation of compression strength. The bearing damage around the fastener holes is also quite difficult to detect visually. To detect these types of damage of the CFRP composites, self-sensing TDR is proposed by Todoroki using a parallel-plate method. Micro-strip line (MSL) method was also proposed in the previous research. The MSL method, however, detects only near the MSL. In the present study, therefore, the MSL method is improved to cover wider area of a CFRP structure using curved MSL method in the first year (Todoroki A, et al., Self-sensing Curved Micro-Strip Line Method for Damage Detection of CFRP composites, Open J. of Composite Materials, 4;3, 2014, 131-139). The self-sensing MSL is applied to detect impact damage of a CFRP plate in the second year (Todoroki A, et al., Impact damage detection of a carbon-fibre-reinforced-polymer plate employing self-sensing time-domain reflectometry, Composite Structures, 130, 2015, 174-179). The research results shows that the impact damages such as fiber delamination and fiber micro-buckling was successfully detected. The self-sensing TDR method using MSL is applied to detect damage around fastener holes. Bearing failure of the fastener hole was detected in the last year. As the metallic fasters affect the transmission line of MSL, the appropriate distance from the metallic fasteners and MSL was obtained using the finite difference time domain simulation method. The newly decided MSL is applied to detect bearing failure around the fastener hole. The method successfully detected the bearing failure. The series of the researches of the self-sensing TDR using MSL enables us to detect damage of large structures with small cost. The self-sensing TDR only requires a transmission line made from two electric conductive structures and a sandwiched insulator material. The self-sensing TDR with MSL is not limited to CFRP structures but can be applied aluminum and steel structures. The newly developed self-sensing TDR can be applied conventional aluminum aircrafts, steel ships and steel bridges to detect fatigue cracks at low cost.

Introduction: Carbon Fiber Reinforced Polymer (CFRP) composites are widely applied to aerospace components because the materials have high specific strength and high specific stiffness. Low velocity impact such as tool drop may cause invisible delamination cracking for the CFRP structures. The delamination cracking may cause degradation of compression strength. Thus, it is very important to detect the delamination cracking caused by impact load to improve the reliability of the composite structures. One of the non-destructive inspection methods is self-sensing technology that uses carbon fibres as sensors [1]-[11]. The self-sensing technology applies electric current to the composite structures and measures the electrical resistance change to detect the damages. Although the self-sensing technique detects precisely damage, the technique requires mounting a lot of electrodes on the CFRP surface. This demands a new method that detects wide area with small number of electrodes.

For many CFRP structures, metallic fasteners are usually adopted to joint many components. For the fasteners used in the internal structures such as a wing box, the damage of CFRP structures around the fastener holes is also quite difficult to find visually. A simple method to find the damage around the fastener holes is, therefore, required for the actual CFRP structures. The actual damage around the fastener holes is reported to be bearing failure mode in the review paper of Thoppul et al [12]. The methods to monitor the bearing failure damage around the fastener holes have been published in several papers. Galea et al [13]. have proposed a method using piezo film. Ihn and Chang have used SMART Layer that uses thin film with distributed piezoelectric sensors [14].

Several researches used Time Domain Reflectometry (TDR) for damage detection [15]-[17]. Authors have developed a self-sensing TDR for detection of fibre breakages using a parallel plate [18] and using a Micro-Strip Line (MSL) [19]. The newly developed method adopts nanosecond order pulse signal, and reflected pulse signal from the fibre breakage can be detected. The method uses carbon fibers as one of structures of transmission line. The method is simulated using Finite Difference Time Domain (FDTD) analysis method [20]. In these previous papers, the detected damage is fibre breakage and unidirectional CFRP ply is adopted.

In the present project, CFRP laminated plates are adopted as a target structure for application of self-sensing TDR. The previous researches [18-20] showed that the self-sensing TDR is applicable for detecting fiber breakages. The parallel plate method is, however, cumbersome for the actual usage. The MSL method is appropriate for the practical use. The MSL, however, can detect damages locates adjacent to the narrow strip line. In the present project, the first objective is to develop a new self-sensing method to cover wider area. Curved MSL method is developed for the self-sensing TDR. The second objective is to detect actual impact damage including delamination cracking. Cross-ply laminated plates are adopted for experiments. The third objective of the present project is to detect bearing failure of metallic fastener holes. To detect the bearing failure, the metal fasteners affect the transmission line of the TDR. To investigate the effect of the metallic fasteners is investigated using a computer simulation method (Finite Difference Time Domain: FDTD) method. After obtaining the appropriate MSL for bearing failure detection, experimental researches are also performed.

Self-sensing TDR:
The TDR method uses a pulse signal in a transmission line. The transmission line comprises of two parallel conductive components and insulator that is sandwiched between the two conductive components. In the case of Fig.1, the micro-strip line (MSL) is the transmission line and the MSL is made from copper foil and CFRP that are electric conductive materials and electric insulator Glass Fibre Reinforced Polymer (GFRP). In the high frequency alternating current such as radio frequency or higher, the electric energy emits from the conductive material to insulator or air. The emitted energy is absorbed in the other conductive material. This process makes a transmission line. Therefore, the transmission line requires two electrically separated conductive components. The sandwiched insulator acts to separate the two conductive components electrically.

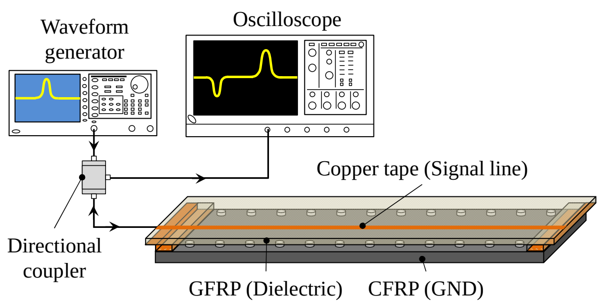

Figure 1 Schematic representation of self-sensing TDR method

The input electro-magnetic wave can propagate in the insulator between the two electric conductive materials: copper foil and CFRP. In the previous paper, we used a parallel plate transmission line [18]. In the case of the parallel-plate transmission line, the air gap between the parallel plates plays a role of insulator, and the CFRP plate and the aluminum plate play a role of conductor.

The pulse signal is input in the transmission line when the impedance of the transmission line is almost equal to that of the normal coaxial cable (50 Ω) which is usually used for measurements. When the characteristic impedance of the transmission line is different from that of the coaxial cable, the pulse signal is reflected at the input terminal of the transmission line.

The pulse signal input in the transmission line propagates in the transmission line. When the transmission line has different characteristic impedance, which comes from carbon fibre damage or change of distance between the two conductive materials because of such as debonding of the insulator or dent, the input signal is reflected at the place. The pulse signal reflected from the transmission line is measured and the result is plotted with the abscissa representing time and the ordinate representing the voltage.

The TDR method requires a wave generator, an oscilloscope, and a target transmission line, as shown in Fig. 1. Figure 1 shows a MSL type transmission line made on the CFRP plate. The wave generator produces a pulse wave signal, which is sent to a directional coupler. The signal propagates only in the MSL type target transmission line because of the directional coupler. Part of the signal is reflected at the input end of the MSL type transmission line because of the slight difference in the characteristic impedance. The other part propagates in the MSL type transmission line. The signal input to the MSL type transmission line is divided into reflection and transmission components at the damaged point. The reflected signal returns and is measured using an oscilloscope. The time difference between the input signal and reflected signal indicates the distance to the damaged point after multiplication by the speed. Using the TDR method, the damage and its location can be measured. The distance L from the input end to the damage is calculated as [21]

$$L = \frac{V_p \Delta T}{2}, \quad (1)$$

where V_p is the transmission velocity and ΔT denotes the time difference between the input signal and reflected signal. The transmission velocity V_p, which is affected by the transmission line, is approximately 0.6–0.9 times the velocity of light. To measure the V_p, the time difference ΔT of the reflected signal between the input terminal and the end terminal is measured, and the transmission line length is set to L in the equation (1). Solving the equation (1) with respect to V_p gives the transmission velocity.

Analytical method:
In the present study, FDTD analysis is adopted to investigate the effect of distance between the electric-conductive fastener and the transmission line. The FDTD analysis solves the well-known Maxwell's equations numerically. As the TDR method uses a transmission line of electro-magnetic waves, solving the Maxwell's equations numerically gives simulated results of self-sensing TDR method. CFRP can be treated as electric conductive material with orthotropic conductivity [18]. The computational method has already shown in the paper [20]. The difference is the boundary condition. In the present study, the absorbing boundary condition proposed by Mur [22] is used to reduce the computational cost at the sacrifice of stability in long time. The computational reliability is confirmed with comparison between the previous results and the new results using Mur's absorbing boundary condition.

The unit cell dimensions for the FDTD analysis is (Δx, Δy, Δz) = (1 mm, 1 mm, 0.2 mm). Time step for the FDTD analysis should satisfy the Courant's stability condition as follow.

$$\Delta t \le \frac{1}{c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \quad (2)$$

where c is the speed of light. To satisfy the Courant' stability condition, the time step is set to Δt=0.5 ps in the present study. The specific magnetic permeability of the entire region is set to μ_r=1.0. The specific dielectric constant of air is ε_r=1.0, and the specific dielectric constant of GFRP is set to ε_r=4.0. The conductivity of copper is 5.96×107 S/m, and the conductivity of CFRP measured by Hirano et al [23] is used in the present study. A pulse signal is input from the left terminal. Figure 2 shows the input Gaussian pulse signal for the FDTD analysis.

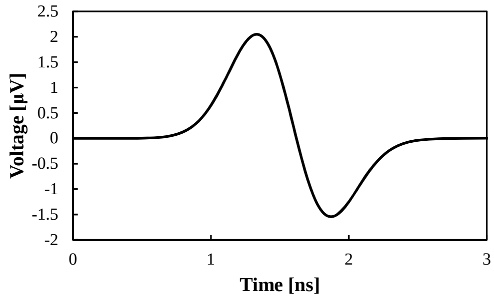

Figure 2 Input signal used for FDTD analysis

Experimental method:

Self-sensing TDR

A MSL type transmission line is used in the present study as shown in Figure 1: a narrow copper strip tape and a CFRP laminate are used as the two conductive materials and a GFRP plate is used as an insulator between the two conductive materials. The characteristic impedance of the narrow-strip transmission line is obtained as shown by Wadell [24].

$$Z_c = \frac{Z_c^a}{\sqrt{\varepsilon_W}} \tag{2}$$

$$Z_c^a = 30\ln\left[1 + \frac{4h}{W_0}\left\{\frac{8h}{W_0} + \sqrt{\left(\frac{8h}{W_0}\right)^2 + \pi^2}\right\}\right]$$

$$\varepsilon_W = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10h}{W}\right)^{\frac{1}{2}} - \frac{\varepsilon_r - 1}{4.6}\frac{t}{h}\sqrt{\frac{h}{W}}$$

$$W_0 = W + \frac{t}{\pi}\ln\frac{4e}{\left[\left(\frac{t}{h}\right)^2 + \frac{1}{\pi^2\left(\frac{W}{t} + 1.1\right)^2}\right]^{\frac{1}{2}}}$$

where h is the height of the dielectric GFRP, ε_r is the relative permittivity of the GFRP, W is the width of the copper strip, t is the thickness of the copper strip, Z_{ca} is the characteristic impedance when the dielectric material is a vacuum and ε_W is the effective value of relative permittivity. Using equations (2), the characteristic impedance of the narrow-strip transmission line can be designed to match the impedance of a coaxial cable of 50 Ω. Without the impedance matching, the input pulse signal is entirely reflected at the input end of the specimen transmission line. Impedance matching is an indispensable procedure for the self-sensing TDR method to detect damage in CFRP structures. As the thickness of GFRP and copper tape is fixed to a small set, the impedance matching to the coaxial cable of 50 Ω means the dimensions of the MSL are almost fixed to narrow bands.

A function generator AFG3251 made by Tektronix Inc.(1ch, Max 240 MHz) is used to generate pulse signal. The amplitude is 5 V and the half-band wise is almost 4 ns. Although the amplitude of the generated pulse signal is 5 V, the amplitude of the input signal is almost 1 V. This is caused by the slight difference of the impedance between the coaxial cable and the self-sensing transmission line: the impedance matching is not perfect for the actual self-sensing transmission line. A directional coupler of ZFDC-10-5 (Mini-Circuit) is adopted to select pulse signal wave reflected from the specimen. To measure the reflected pulse signal, oscilloscope TDS5034B (Tektronix, sampling 0.02 ns) is used. Copper mesh strip of 0.16 mm thickness (wire diameter is 0.08 mm, equivalent conductance that is calculated from the volume fraction of copper wire is 1.5×10^7 S/m). To input pulse signal into the transmission line, the impedance of the transmission line must be matched with coaxial cable to prevent reflection of impedance mismatch.

Specimen configuration of curved self-sensing TDR

Figure 3 shows the specimen configuration used in the curved self-sensing TDR : the length is 1600 mm, the width is 200 mm and thickness is 2.6 mm. Stacking sequence of the CFRP plate is quasi-isotropic $[0/+45/0/-45/90/+45/0/-45/90]_S$. The material used to fabricate the CFRP laminate is Toray T800S/3900-2B prepreg (180°C×2hr×0.59MPa). After fabricating the CFRP laminate of 1600 mm length, a GFRP laminate of 1 mm thickness (1590 mm length and 200 mm width) is attached on the CFRP laminate as dielectric material using epoxy adhesive. For a transmission line, a couple of conductive material is required. For the another conductive material, copper tape of 2 mm width (0.025 mm thickness) is used to make a curved MSL. The impedance of the MSL is 49.6 Ω. At the curved part of the transmission line, copper plate of the same thickness is used and connected with soldering. As mentioned before, the spacing between the two lines must be four times larger than the width of the strip. In the present study, therefore, the inner diameter of the curved part is 9 mm.

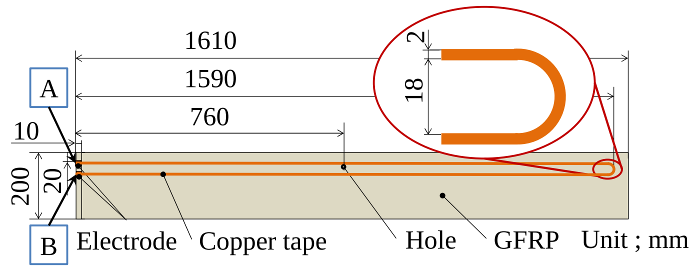

Figure 3 Specimen configuration of curved self-sensing TDR

To obtain the low electrical contact resistance at the input terminal of the CFRP laminate, an electric copper plating method is used. At the input end of the transmission line, the CFRP laminate is used as electric ground and the copper strip is used as a signal line. Copper mesh strip of 0.16 mm thickness (wire diameter is 0.08 mm, equivalent conductance that is calculated from the volume fraction is 1.5×107S/m).

As damage, a mechanical hole is made using a drill of 6 mm diameter at the 760 mm distance from the input end. The edge of the hole is 1 mm distance from the copper strip line edge. This is named type A damage in the present study. After measurements, the drill hole was extended to the edge of the copper strip using filing. This is named type B damage. These two types of model damage are experimentally investigated.

Specimen configuration of impact damage tests

A prepreg IM600/133 (Tohotenux Co. Ltd., Japan) was used, from which a CFRP plate was fabricated with a stacking sequence of [0/90]s. To cure the long specimen, four sheets of silicon rubber heater SRH640 (152mm×1016 mm, Sakaguchi E.H VOC Corp., Japan) are used. The specimen was sandwiched between aluminum plates of the same size. Glass fiber heat insulating materials were used to keep the specimen at 180 °C for two hours. The specimen is 1980-mm-long CFRP plate and 120-mm wide (thickness 0.6 mm) as shown in Fig.4. During the cure, 32 vises are used to apply pressure of approximately 0.55 MPa on the specimen. After the curing, copper electrode is made on the specimen edge to apply electric pulse signal using copper plating method. A BNC cable is soldered to the copper plating electrode.

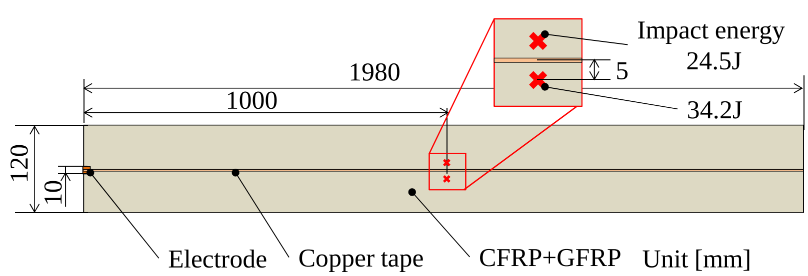

Figure 4 Specimen configuration of impact damage test

Three types of drop-weight impact load are applied to the specimen. The first one is applied on the strip line. The first impact load is applied on the line at 600 mm point from the specimen edge. The impact energy is 14.1 J (weight 3.19 kg × 0.45 m height). The impactor is a hemisphere of diameter of 14 mm made by stainless steel. As the specimen is thin, a GFRP plate of 2 mm thickness is attached to the backside of the CFRP plate to prevent penetration of the impactor. The impact load is applied on the CFRP surface, and after the impact load the MSL is mounted to prevent fracture of the transmission line of the MSL. Of course, when the MSL is damaged as a transmission line, the damaged point reflects the pulse signal. In the present study, to investigate the ability of detection of the impact damage using a self-sensing TDR method, the impact load on the MSL line is applied before mounting the MSL on the CFRP specimen.

The second and third one are applied besides the strip line but the impact energy is different. The impact load location is shown in Fig.4. The impact load is applied from the 5 mm distant apart from the center of the MSL. Two types of impact energy are applied: 24.5 J and 34.2 J as shown in Fig.4.

Specimen configuration of bearing failure of fastener hole

Figure 5 shows the dimensions and configuration of the specimen. The specimen is 1750 mm long, 200 mm wide and is 2.6 mm thick. The material used to fabricate the CFRP laminate is Toray T800S/epoxy prepreg (cure temperature 180° C). The stacking sequence of the CFRP plate is [0/45/0/-45/90/45/0/-45/90]s. On the CFRP specimen, a GFRP fabric plate of 1730 mm long, 200 mm wide and 0.5 mm thick is attached using commercially available epoxy adhesive. On the GFRP plate, copper tape of 5 mm wide and 0.025 mm thick is attached as shown in Figure 5 to build two micro-strip lines. The triangle symbols indicate the location of fasteners of 6.35 mm diameter. The spacing of fasteners is 143.2 mm in the specimen.

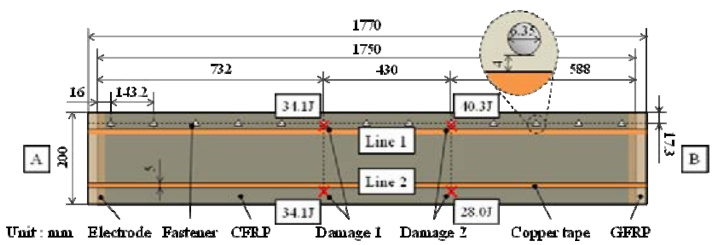

Figure 5 Specimen configuration of bearing failure of fastener hole

Two micro-strip lines are made on the specimen. The line #1 is placed closed to the fasteners (distance between the fasteners and the line 1 is 4 mm). The line #2 is placed far from the fasteners to compare the results. The left terminal is named “terminal A” and the right terminal is named “terminal B” in the present study. Using both terminals, the relationship between the location of the fastener and the location of the damage is experimentally investigated. At the measurements, the other terminal is set to open end. To prevent specimen warping, L type aluminum stiffeners of 1750 mm long and 30 mm wide are attached on the back side.

Bearing fracture damage is made at 732 mm (Damage #1) and 1162 mm (Damage #2) from the terminal A. Bearing failure of a fastener hole of a CFRP plate is usually caused by excessive loading, fatigue loading or initial defects. It is, however, quite difficult to make bearing failure at a fastener hole edge for this large specimen using a normal material testing machine. In the present study, therefore, a drop weight type loading is adopted to make a simulated bearing fracture. For the line #1, the impact energy of 34.1 J is added to the Damage #1, and the impact energy of 40.3 J is added to the Damage #2. For the line #2, 34.1 J is added to Damage #1 and 28.0 J is added to Damage #2. The impact load is applied to the direction of the MSL.

The measurements of reflected pulse signal are performed in three conditions as follows.
Condition #0: intact specimen.
Condition #1: Damage #1
Condition #2: Damage #1 and Damage #2

Results and Discussion:

Curved self-sensing

Figure 6 shows the measured results of reflected signal without damage. The abscissa is the time and the ordinate is the measured voltage of the reflected signal. The input arrow means the position of the end of the time zone affected by the input terminal. The end arrow means the position of the start of the time zone affected by the end terminal. The time zone between the input arrow and the end arrow is, therefore, the measured gage area. The curve arrow means the location of the curve that is calculated from the time difference. Although the radius of the curved strip is four times larger than the width of the copper strip, the small refection is observed at the start point and the end point of the curved copper strip. The both reflection from the start point and the end point of the curved copper strip means that the signal is reflected at the soldering point. As there is no signal reflection at the middle in the curved point, it is understood that the electrical resistance difference between the fiber direction and the transverse direction at the CFRP surface does not affect the TDR method. When a perfectly connected curved MSL is used, the curved MSL is effective for damage detection.

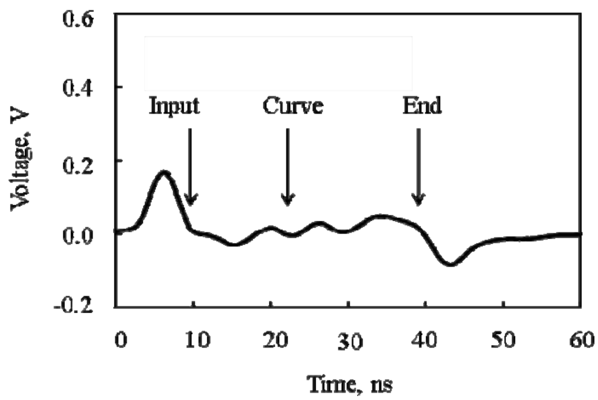

Figure 6 Measured reflected pulse signal from the curved MSL without damage.

Figure 7 shows the measured results of the type A damage. The abscissa is the time and the ordinate is the voltage difference between the intact result shown in Fig.6 and the results with type A damage. As shown in Fig.6, there are many noise reflected signals, and the reflected signal from the damage is not clearly observed.

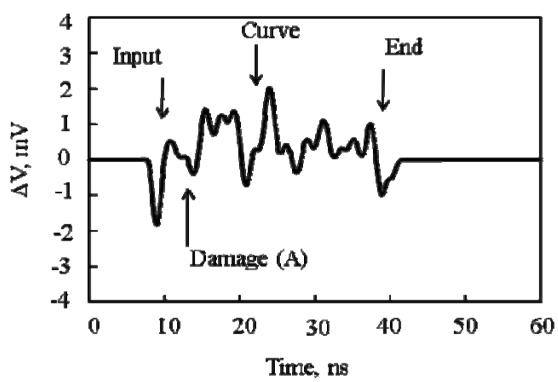

Figure 7 Measured reflected pulse signal difference from the curved MSL with damage type A.

Figure 8 shows the measured results of the type B damage. At the damage expected point, the clear reflected signal is observed as shown in Fig.8. This indicates that the damage closed to the copper strip line can be detected by using the self-sensing curved MSL method.

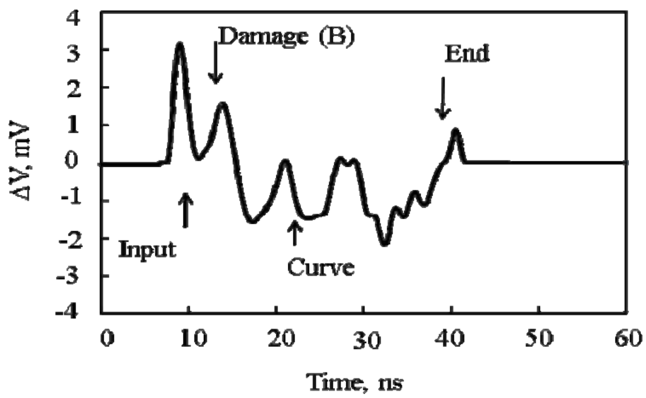

Figure 8 Measured reflected pulse signal difference from the curved MSL with damage type B.

Impact damage test

Figure 9 shows the measured reflected pulse signal of the first experiment: impact load is applied on the exact line of the MSL although the copper mesh was removed when the impact load was applied. The abscissa is time and the ordinate is the measured signal voltage. The dark solid curve is the reflected signal of the intact specimen, and the light solid curve is the reflected signal of the specimen after the impact load at the center of the MSL. In the time segment from 0 ns to 7 ns, the signal is the reflected from the input terminal (left gray area). In the time segment from 20 ns to 30 ns, the signal is the reflected from the specimen end (right gray area).

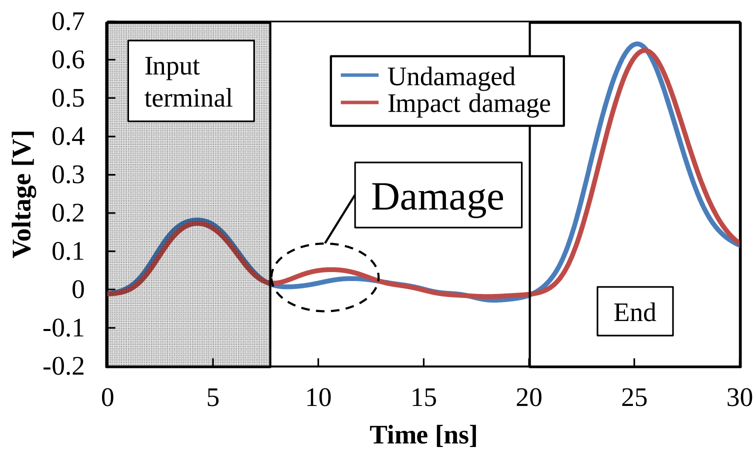

Figure 9 Measured reflected signal of the first impact load test compared with the reflected signal of the intact specimen.

The signal from 7 ns to 20 ns shows the reflected signal from the specimen end. At approximately 10 ns, the light curve has reflected signal. This indicates that the dent and fibre breakages at eh edge of the dent can be detected with the self-sensing TDR method. From the time difference between the peaks of the input terminal and specimen end terminal, we can calculate the signal speed. Using the calculated speed, we can calculate the location of the damage that shows reflected signal. The estimated damage location is 0.58 m. The exact location of the impact load is 0.6 m. This means the self-sensing TDR gives excellent estimation of the damage when the damage locates under the MSL.

Figure 10 shows the measured the difference from the intact specimen. The ordinate is the voltage difference. As shown in Fig.10, the results of higher impact energy of 34.2 J shows the clear reflected signal at approximately 15 ns. However, the results of lower impact energy of 24.5 J show no clear reflected signal. When the damage is apart from the MSL by several mm (similar to the width of the

MSL), the self-sensing TDR method does not detect the damage apart from the MSL. The curved MSL shown enables us to detect damage of wider area although the spacing between the MSL is blind area for the MSL. This is improved when the wider MSL is adopted.

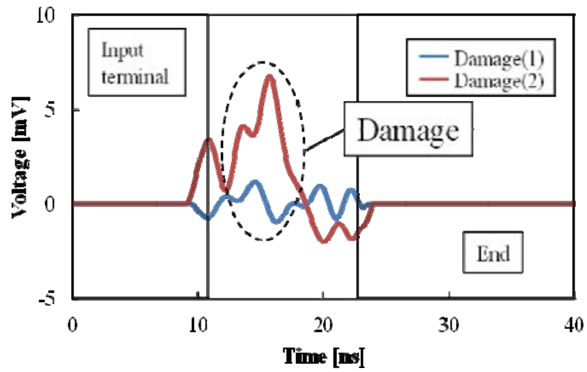

Figure 10 Difference of reflected signal of the second and the third impact load to that of the intact specimen.

Bearing failure of fastener hole
Figure 11 shows the results of reflected signal calculated at the input terminal using FDTD. The abscissa shows the time and the ordinate shows the voltage. The broken curve represents the reflected signal of the specimen without fasteners. As shown in Figure 11, when the fasteners approach the MSL, the amplitudes of the reflected signals decrease. For example, the nearest case of h=1 mm has only 11 % of amplitude compared with the amplitude of the reflected signal without fasteners. The decrease of signal amplitude is caused by the scatter of electromagnetic wave at the metallic fasteners. When h=4 mm, the amplitude of the reflected signal is 92 %. The results represents that the *h*=4 mm is minimum requirement of distance between the fasteners and the MSL of these dimensions.

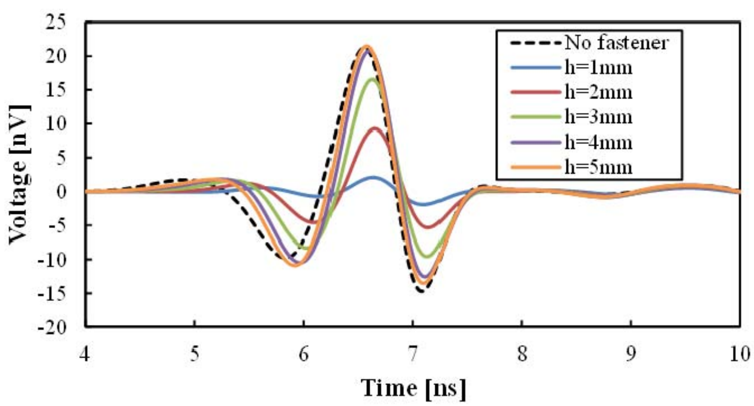

Figure 11 Reflected signal of FDTD analysis: effect of distance between the fasteners and the micro-strip line

Figure 12 shows the difference of the reflected signal between the condition #0 and the condition #2 from the terminal A. Figure 12 indicates that the self-sensing TDR method detects the bearing failure at fastener holes without the effect of fasteners. Figure 13 shows the difference of the reflected signal between the condition #0 and the condition #w from the terminal B. Comparing with the Figure 12, both damages can be monitored without the dependence on the order of damages. The results indicates that the self-sensing TDR method is applicable for the bearing failure monitoring without considering pass of the MSL.

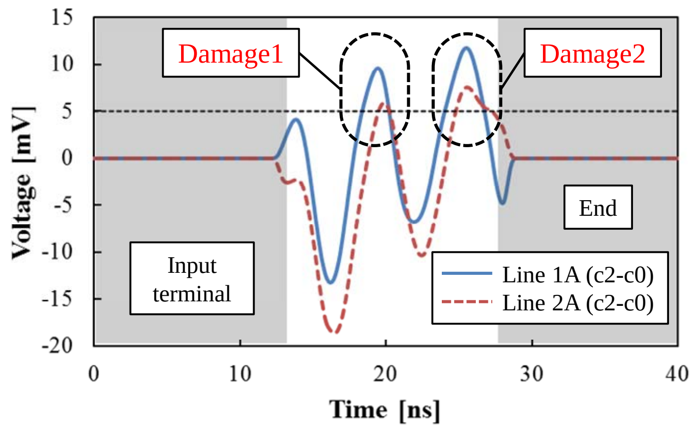

Figure 12 Reflected signal difference from the condition #0 of the results of the condition #2 from the terminal A.

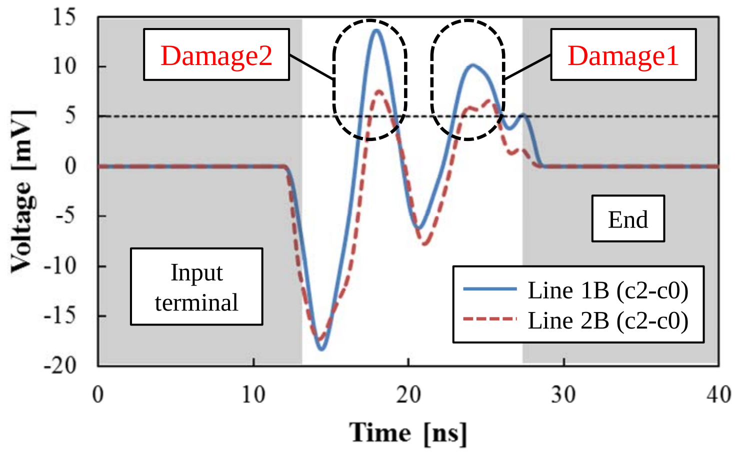

Figure 13 Reflected signal difference from the condition #0 of the results of the condition #2 from the terminal B.

Using the measured signal velocity and the time difference of the reflected signal, damage location can be identified. The estimation error was within 7 % for all cases. These results indicates that the fasteners have no effect on the identification of bearing failure of fastener holes when the distance h (distance from the metallic fastener to the MSL) is set to 4 mm for self-sensing TDR method.

The self-sensing TDR with MSL is applicable for any kinds of electric conductive structures such as aluminum alloy, titanium alloy and steel. When the self-sensing TDR is applied to the metallic materials, the method detects fatigue cracks in the entire structure. As the fatigue crack causes the impedance change, the fatigue crack is surely detected by this method. Using the curved self-sensing TDR, the method can be applied to wide area of the structures. This indicates the method can be applied to conventional aircraft made from aluminum alloy at low cost. In addition, the method can be applied to ships or bridges to detect damages or fatigue cracks as well as CFRP composite structures.

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Electrical Resistance", J. American Ceramic Society, Vol.76, No.4, 1993, pp.875-879.
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List of Publications and Significant Collaborations that resulted from your AOARD supported project:

Published papers

[1] Akira Todoroki, Kazuhiro Yamada, Yoshihiro Mizutani, Yoshiro Suzuki, Ryosuke Matsuzaki, Hiroyasu Fujita, Self-sensing Curved Micro-Strip Line Method for Damage Detection of CFRP composites, Open Journal of Composite Materials, Vol.4,No.3,(2014) ,pp.131-139

[2] Akira Todoroki, KazuhiroYamada, Yoshihiro Mizutani, Yoshiro Suzuki, Ryosuke Matsuzaki Impact damage detection of a carbon-fibre-reinforced-polymer plate employing self-sensing time-domain reflectometry, Composite Structures, 130, (2015), pp.174-179.

[3] Akira Todoroki, Keisuke Ohara, Yoshihiro Mizutani, Yoshiro Suzuki, Ryosuke Matsuzaki, Self-sensing TDR for bearing failure detection of CFRP laminate fastener hole with particular reference to the effect of fasteners, Open Journal of Composite Materials (in press).